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Advection and the estimation of irrigation need

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1. Introduction

Irrigated crops growing in isolated fields in an otherwise arid or semi-arid region transpire at relatively high rates, using advected sensible heat to supplement the radiational source of energy. The heat is drawn from a progressively deeper layer of air as the fetch across the watered field increases and in many cases a temperature inversion develops over the crop beyond a certain fetch. At the same time water evaporated from the crop moistens the air in the surface layer, decreasing the humidity deficit, and therefore causing a progressive reduction in evapotranspiration with increasing fetch across the field. Traditionally the estimation of irrigation need involved the use of the combination equation in conjunction with standard meteorological data obtained over an unwatered grass surface, using a value for the bulk stomatal resistance appropriate to a crop freely supplied with water. The unwatered grass, if it is experiencing the effects of a substantial soil moisture deficit, will be significantly warmer than an irrigated crop, with a correspondingly larger humidity deficit in the air above it. Clearly it is entirely fortuitous if this traditional estimate of irrigation need matches closely the evapotranspiration of the watered crop. This present memorandum discusses some of the observational evidence for the effects of advection on evapotranspiration and concludes with an attempt to use existing theories of advection to obtain more reliable estimates of water loss from irrigated crops.

2. Brief review of some experimental results

The characteristic diurnal variation of air temperature is, during the first part of the day, an increase from about sunrise to early or mid-afternoon. This increase can only occur over a homogeneous area of substantial size if there is an upward flux of sensible heat from the surface to warm the air above which in turn demands that the vertical flux of water vapour must be less than the available energy. Any situation during this warming period in which this vapour flux is larger than the available energy is a certain demonstration of advection: less-extreme advection will also occur when the upward water vapour flux, while less than the available energy, is larger than the value expected to be observed regionally. On this basis a number of studies have demonstrated the results of advection. Rosenberg (1969) found from lysimeter measurements in an irrigated plot of alfalfa (0.25 m high) 60 m in diameter in a 2 ha field of the same crop that evaporation exceeded available energy by about 60%. Evans (1971) measured evaporation rates from a lysimeter in an irrigated rice crop, at least 200 m from the edge of the field which was situated in an arid region. The average ratio of evaporation to available energy was about 1.7. A similar ratio was found by McIlroy and Angus (1964) using a lysimeter in an irrigated field of short grass about 100 m square for occasions when the surrounding area had not been wetted recently by rain.

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A number of studies have investigated the variation of evapotranspiration with increasing distance downwind of the leading edge of the irrigated area (eg Hudson (1962), Rider et al (1963), Millar (1964), Dyer and Crawford (1965), Davenport and Hudson (1967), Goelt and Pruitt (1970), Decker (1970), Lang et al (1974) and Brakke et al (1978)). Most of these irrigated plots were in arid areas. All these studies have demonstrated the expected decrease of evapotranspiration with increasing distance (§ 1) but by amounts which varied considerably between the experiments. The lack of consistency is to be expected because the relative effects of advection will vary with wind speed, humidity deficit, crop roughness and available energy. However in all cases the flux fell off very rapidly with distance close to the upwind edge. For example Rider et al (1963) working over irrigated grass downwind of tarmac estimated the average water vapour fluxes between 0 and 1 m, 0 and 4 m and 0 and 16 m from the edge of the grass were approximately 4.0, 2.8, and 1.9 times larger than the available energy measured over the grass. They also noted that the available energy over the grass was substantially larger (by about 50%) than over tarmac, partly because of the lower surface temperature of the grass, but also because the soil heat flux under the grass was less. Dyer and Crawford (1965) showed that in a situation with high available energy ($\sim 400\ Wm^{-2}$) and only moderate advection ($U_{1.0} \sim 6\ ms^{-1}$) the water vapour flux decreased by only 4% between 15 m and 150 m from the leading edge of an irrigated field of grass: here the flux was less than 10% larger than the available energy. In contrast, measurements in a situation with low available energy ($\sim 100\ Wm^{-2}$) and strong advection ($\sim 11\ ms^{-1}$) showed a 40% decrease in flux between 25 m and 150 m, with the flux at 25 m about 3 times the available energy. In cases like the latter a considerable amount of energy has to be extracted from the lower atmosphere, producing a temperature inversion which will inhibit vertical mixing and so cause the observed rapid reduction in evapotranspiration with increasing distance downwind.

Some results presented by Davenport and Hudson (1967) are of interest because they were obtained in a temperate climate (in England). Evapotranspiration was estimated to decrease by 13% from near the leading edge of a field of transpiring sugar beet to a point 40 m downwind: the field was surrounded by "dry barley stubble".

3. Theoretical treatments

The various observational studies which have been mentioned, while presenting ample evidence for the effects of advection, are inadequate as a basis for predicting advection effects under any set of meteorological conditions. However there are a number of theories of advection which, in principle at least, may be applied to the problem of estimating water loss from irrigated crops. A full treatment of the problem will include the effects of change of surface roughness across the boundary, and the change of available energy. Theories presented by De Vries (1959), Philip (1959), Rider et al (163), Yeh and Brutsaert (1971) and McNaughton (1976) have various deficiencies, although some have been shown to give, in restricted applications, moderate agreement with experimental results. At present the only theory that has sought to include a proper dynamical modelling of the turbulent exchange processes which are involved in advection is that by Rao et al (1974). Their model includes as a lower boundary condition a constant relative humidity, although this may not be a very serious practical limitation. It uses exact equations for the mean quantities and a full set of turbulence equations which are closed by higher order approximations. The model solution is not entirely straightforward and was carried out for one case only, to simulate the experimental results of Rider et al: a close match between measured and calculated temperature and humidity profiles was obtained. The lack of generality

of results from the model precludes its application to the general problem of estimating irrigation need since for each meteorological situation the complete set of equations has to be solved by numerical methods.

McNaughton (1976) produced a treatment which, while simpler and much less rigorous than that of Rao et al, is in principle applicable on a routine basis to the calculation of irrigation need. This theory ignores roughness changes across the field boundary and assumes identical values for the eddy diffusion coefficients for momentum, heat and water vapour. Use is also made of the observation that in a quasi-equilibrium (non-advection) situation the water vapour flux may be approximated by

$$\lambda E = \frac{f \Delta' (R_N - G)}{\Delta' + c_p/\lambda} \qquad (1)$$

where

$$\Delta' = \partial q_{(sat)}/\partial T$$

c_p = specific heat of air

λ = latent heat of vapourisation

$R_N - G$ = available energy

$f \sim 1$

With these assumptions McNaughton derived the following expression for the latent heat flux under advective conditions:

$$\lambda E = \frac{\Delta'}{\Delta' + c_p/\lambda} (R_N - G) + \frac{\Delta'}{\Delta' + c_p/\lambda} \left(\frac{1}{r_s} \left(r_s' (R_N' - G') - r_s (R_N - G) \right) \right) \Phi_x \qquad (2)$$

where

r_s = bulk stomatal resistance

x = distance downwind of edge of irrigated plot

$\Phi_x = fn \left(\frac{c_p/\lambda}{\Delta' + c_p/\lambda} u_* r_s, \; x/z_o \right)$

u_* = friction velocity

z_o = surface roughness length

(Δ' refers to the irrigated plot: otherwise primes refer to values upwind of plot).

The second term on the right hand side of Eq (1) is the advective enhancement of evaporation. The approximations in the theory do not justify any attempt to define the atmospheric stability with high accuracy, and neutral conditions will be assumed therefore. On this basis

$$u_* = 0.4 U_{10} / \ln (10/z_o) \qquad (3)$$

where U_{10} is the 10 m wind speed. McNaughton's treatment showed that the function Φ_x may be approximated over typical ranges of x/z_o by

$$\Phi_x = (0.143 + 0.101 \ln A + 0.098 (\ln A)^2 - 0.019 (\ln A)^3)$$

$$- (0.0084 + 0.0051 \ln A + 0.0056 (\ln A)^2 - 0.0018 (\ln A)^3) \ln\left(\frac{x}{z_o}\right) \quad (4)$$

where

$$A = \frac{c_p/\lambda}{\Delta' + c_p/\lambda} u_* r_s \quad (5)$$

The theory may be applied to a case with low humidity, with the following values for the meteorological variables:

U_{10} = 5 ms^{-1}

$R_N - G = R_N' - G'$ = 200 Wm^{-2}

T = 20 deg C

$\delta q'$ = 0.010 (specific humidity deficit over stressed area)

r_s = 40 sm^{-1}

r_s' = 1000 sm^{-1}

z_o = 0.01 m

Then,

$A = 3.6$

and

λE (x = 1 m) = 138 (1 + 24 Φ_x) = 1123 Wm^{-2}

λE (x = 10m) = 969 Wm^{-2}

λE (x = 100 m) = 813 Wm^{-2}

These relative rates of evaporation at the three distances are similar to those found in a number of the experimental studies mentioned earlier, but the absolute values appear to be very large. The results are biased however by the assumption that $R_N - G = R_N' - G'$. Surface temperatures over the water-stressed upwind area will be about 6 deg C higher than screen temperature (Thompson 1978): soil heat flux will also be larger there because of the greater amplitude of the surface temperature diurnal wave (e.g. Rider et al 1963). Over the irrigated plot a temperature inversion is likely to be present. As a result $R_N' \sim 0.8\, R_N$ and $R_N' - G' \sim 0.7 (R_N - G)$, and assuming now that $R_N - G$ = 200 Wm^{-2} then leads to latent heat fluxes of 821, 713 and 607 Wm^{-2} at 1 m, 10m and 100 m respectively. These revised values are still very large and it appears therefore that the theory's approximations prevent its application in a quantitative rather than qualitative sense. The major flaw in the formulation

appears to be that the advective enhancement is almost directly proportional to r_s'/r_s when this ratio is appreciably larger than 1. Thus a small change in aridity upwind (say r_s' increasing from 1000 to 2000 sm^{-1}) is calculated to roughly double the evaporation at a fixed distance downwind from the edge of the irrigated plot. This is obviously at variance with experimental results where even with extreme aridity ($r_s' \gg r_s$) the evapotranspiration over the irrigated plot a few tens of metres from its edge is only about twice the equilibrium value.

(Routine calculations of irrigation need (eg MORECS) assume that screen and surface temperature are the same, so the available energy for the present case would be 200 Wm^{-2}, and then apply the combination formula using values measured over unirrigated grass, with a value for r_s appropriate to the unstressed crop. In this instance this leads to a flux of latent heat over the irrigated crop of 250 Wm^{-2} compared with 55 Wm^{-2} over the unwatered crop. The equilibrium flux over the irrigated crop, which is reached after sufficiently long downwind travel is about 150 Wm^{-2}, and this will certainly be exceeded by a substantial amount over small plots with short fetch. The MORECS estimate is (correctly) larger than the equilibrium value but can only indicate accurately the water loss at a single (unknown) distance downwind from the leading edge of the plot).

The theory of Philip (1959) treated the case with non-zero evapotranspiration upwind of the boundary by introducing the mathematical device of a non-zero "equilibrium" flux, assumed to occur uniformly both upwind and downwind of the edge of irrigation. His solutions were obtained by superposing the calculated advective flux on this background flux. By this means Rider and Philip (1960) obtained an expression for the Bowen ratio (B_o) over an effectively saturated surface

$$B_o = \frac{B_o' - \alpha\,(1+B_o')^2}{(R_N-G)x^{1/9} + \alpha(1+B_o')} \qquad (6)$$

where α is a constant determined by the upwind temperature and humidity and B_o' is the Bowen ratio over the upwind surface. Clearly B_o returns (incorrectly) to its upwind value for large fetch x over the irrigated area. The treatment on which (6) depends was developed by effectively decoupling the diffusion of heat and water vapour whereas these two processes are strongly coupled through the energy balance at the surface. The one-ninth power of fetch arises through the use of power-law formulations for the wind profile, with the power set equal to 1/7 (appropriate for neutral conditions). The form which α takes was not given by Rider and Philip and so (6) cannot be used conveniently in practice.

Philip's (1959) model was tested by Decker (1970) against results obtained by a lysimeter located 100 m downwind in an irrigated grass field. Results agreed fairly closely when an advective inversion existed over the field but where there was no inversion lysimeter evaporation was 30-80% higher than model values. The theory does not appear to be satisfactory for general applications therefore. In any case the calculation involved using the difference in specific humidity at the upwind and downwind surfaces, a quantity not available in MORECS-type calculations.

De Vries (1959) developed a theory of advection along rather similar lines to those of Philip, again with the assumption of saturation at the downwind surface, but presenting his results as (simple) asymptotic solutions for small and large values of x (instead of Philip's Γ functions): in addition application of his results required only a rough specification of the surface temperature over the irrigated plot. The expansions for small and large x were respectively

$$I = I' + \frac{d}{a_1 + sD_1}\left((\pi\xi)^{-1/2} + \tfrac{1}{4}(1+m) + B - (1+m)\beta_1\right) \qquad (x \text{ small}) \quad (7)$$

$$I = I' + \frac{(1+m)d}{a_1 + sD_1}\left\{\frac{1}{\ln \xi'/C}\left[1 - \frac{0.5772}{\ln \xi'/C} - \frac{1.312}{\ln^2 \xi'/C} + \frac{0.252}{\ln^3 \xi'/C} + \frac{3.997}{\ln^4 \xi'/C}\right.\right.$$

$$\left. + \frac{5.064}{\ln^5 \xi'/C}\right] + \left(\tfrac{1}{2}\beta - \beta_1\right) - \beta_1\left(\tfrac{1}{2}\beta - \beta_1\right)\ln \xi'$$

$$\left. + \beta_1^2\left(\tfrac{1}{2}\beta - \beta_1\right)\left(\ln^2 \xi' - \pi^2/6\right)\right\} \qquad (x \text{ large}) \quad (8)$$

where I = evaporation from irrigated plot (metres depth of water s^{-1})

I' = upwind evaporation

d = difference between surface temperature and surface dewpoint for upwind surface (deg C)

$a_1 \simeq 830 z_1 \lambda / (c_p K_0)$ $\quad sm^{-1}$ deg C

$s = \dfrac{\partial T}{\partial q_{(sat)}}$ (T = mean surface temperature of irrigated plot) deg C

$D_1 \simeq 830 z_1 / K_0$ $\quad m^{-1}s$

$\xi' = (1+m)^2 \xi / C$

$\xi = K_0 x / (z_1^2 u_0)$

$C = 1.781$

$m \simeq 1/7$

$B = 4 z_1 \epsilon \sigma T_{0_{upwind}}^3 / \rho_{air} c_p K_0$

$\beta = 2B/(1+m)$

$\beta' = \tfrac{1}{2}\beta s D_1 / (a_1 + sD_1)$

$T_{0_{upwind}}$ = surface temperature of upwind surface

ρ = air density ($\simeq 1.2$ Kg m^{-3})

$c_p = 1005$ J Kg^{-1} K^{-1}

$\lambda \simeq 2.46 \times 10^6$ J Kg^{-1}

ϵ = long wave emissivity of surface (~ 1)

$u = u_0 (1 + z/z_1)^m$ wind speed at height z

$K = K_0 (1 + z/z_1)$ eddy diffusion coefficient at height z

The results of de Vries' theory include specifically a correction for the different radiation balances over the dry and irrigated surfaces. It is seen that practical applications of the formulae require estimates of surface temperature and surface dewpoint over the dry area, and specification of K_o, u_o and z_1. Surface temperature over the irrigated plot (from which s is determined) can probably be equated to the standard observations of screen temperature with little error. Surface temperature and dewpoint over the upwind plot may be determined roughly from screen observations, wind speed and the energy balance by first calculating the vertical flux of water vapour using the combination formula, and then using the definition of aerodynamic resistance

$$r_a = \rho c_p (T_o - T_{screen})/H \qquad (9)$$

$$r_a = \rho (q_o - q_{screen})/E \qquad (10)$$

$$r_a \simeq \frac{6.25}{u_{1.2}} \ln\left(\frac{1.2}{z_o}\right) \ln\left(\frac{1.2}{0.2 z_o}\right) \qquad (11)$$

where z_o = roughness length ($\sim$ 0.01 m for grass around an instrument enclosure)

$u_{1.2}$ = wind speed at screen height - the assumption of neutral stability has been used

(11) may be rewritten for the case where wind is measured at 10 m height:

$$r_a = \frac{6.25}{u_o} \ln\left(\frac{10}{z_o}\right) \ln\left(\frac{6}{z_o}\right) \qquad (12)$$

Application of (9), (10) and (12) using the values for the variables which were applied earlier in the verification of McNaughton's theory leads to a surface temperature of 24.6 deg C (instead of $\sim$ 26 deg C given by a fully diabatic treatment) and a dewpoint depression of 20.2 deg C. Putting z_1 = 0.01m gives values for u_o and K_o of 1.86 ms^{-1} and 1.16 x 10^{-3} m^2s^{-1}. The following values for the variables in Eq (7) and (8) are calculated therefore

a_1 = 1.75 x 10^{-7} sm^{-1} deg K

d = 20.2 deg C

s = 1111 deg C

D = 7155 $m^{-1}s$

ξ = 6.24

ξ' = 4.58

β = 0.0428

β_1 = 0.0117

$(\frac{1}{2}\beta - \beta_1)$ = 0.0147

$I \simeq 40\ Wm^{-2} \equiv 1.62 \times 10^{-8}\ ms^{-1}$

Application of Eq (7) at distances up to 1 m, and Eq (8) for distances greater than a few metres leads to the following values for

x =	0.1 m	1 m	10 m	100 m	1000 m
$I-I'$ (Wm^{-2})	2014	1390	574	399	310

de Vries' assumption of saturation at the surface of the irrigated crop leads to overestimation of the fluxes but using an empirical factor of 0.8 (similar to that used by Penman) to convert roughly to evaporation from unsaturated, unstressed, surfaces leads to the following corrected estimates for plot evaporation

x =	0.1 m	1 m	10 m	100 m	1000 m
$I-I'$ (Wm^{-2})	1611	1112	459	319	248
I	1651	1152	499	359	288
$I/(R_n-G)_{irrigated}$	8.25	5.76	2.50	1.80	1.44
$I/$MoRECS	6.60	4.61	2.00	1.44	1.15

These last calculated values are at least roughly consistent with the few experimental data on plot evaporation during advection with very dry air. Any better than a rough fit to observations is not to be expected because of

(i) the assumption of equality in the diffusion coefficients for heat, water vapour and momentum, over both dry and irrigated surface.

(ii) neglect of different roughness lengths for the two surfaces.

(iii) The approach at large distances downwind to the upwind value of evaporation (with a correction for the difference in available energies over the two surfaces) instead of to the equilibrium value appropriate to the irrigated surface: this may not be a serious limitation of the theory in UK situations where irrigated plots are small usually.

On several counts then the theory must be expected to give inexact quantitive estimates of the effects of advection on plot evaporation. However the evidence from the theories for very high rates of evaporation close to the upwind edge of irrigated plots in arid surroundings is consistent with experimental results.

4. Conclusions

Theory and experiment agree in demonstrating the importance of advected energy in controlling evaporation over well-watered fields downwind of more arid surfaces. Simple theories of advection such as those of McNaughton, Philip and de Vries have a variety of shortcomings and almost certainly cannot be applied in real situations to estimate irrigation need without empirical corrections. Such corrections could probably be obtained by using results from lysimeters at the centres of irrigated plots of different sizes (say 5 m, 50 m and 500 m diameter), but an experiment of this nature would need to continue for several seasons in order to include cases with a range of roughness lengths for the dry and watered surfaces, and a wide range of advected energy. On the other hand the simple theories can probably be used to give a moderately good estimate of the very high evaporation close to the irrigated edge.

Clearly crops on the upwind edge of watered fields are likely to be grossly underwatered in drought situations unless irrigation is extended to the surface upwind, say 10-30 m from the crop in order to provide an adequate "guard-strip".

The most economical method of improving estimates of irrigation need is likely to be the application of more advanced theories such as that of Rao et al (1974) to a realistic range of meteorological and crop conditions, with experimental verification by a limited number of field measurements selected by a sensitivity analysis of the model. Britain's climate is probably not arid sufficiently often for the experimental parts of such a study to be carried out here.

Any comments or suggestions on this paper should be referred to the authors.

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